On Reliability Modeling in Wireless Sensor Networks-A Review

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Abstract

This paper presents a survey on existing reliability models in wireless sensor networks (WSNs). Most of the existing mechanisms employ retransmissions, ignoring redundancy schemes and moreover no attempt has been made for biologically inspired WSNs. This paper proposes a biologically inspired wireless sensor network model where sensor nodes are intelligent enough to recall the desired information despite of corrupted information sensed. We finally pointed out some of the future research directions and challenges ahead to improve the reliability in WSNs.

Keywords: **WSNs, BS, Reliability, QoS, GPS.**

1. Introduction

Wireless Sensor Networks (WSNs) have the potential of revolutionizing the way wireless technology has been used over the decades. WSNs have enjoyed considerable interest from the research community due to their varied applications and unique challenges. A key functionality of WSNs consists in obtaining and transporting the information of interest (e.g., events/status) required by the different applications having varied requirements on the reliability and timeliness of data delivery. While node redundancy, inherent in WSNs, increases the fault tolerance, no guarantees on reliability levels can be assured. Furthermore, the frequent failures within WSNs impact the observed reliability over time and make it more challenging to achieve the desired reliability. Unfortunately, a framework for modeling reliability of data transport protocols in WSNs is currently missing. In data gathering WSNs, data loss often happens due to external faults such as random link failures and hazard node faults, since sensor nodes (SNs) have constrained resources and are often deployed in inhospitable environments. Failing nodes alter the topology of the network resulting in segmented routing paths and lost messages, ultimately reducing network reliability.

Historically, WSNs have been characterized as wireless networks consisting of numerous small, energy constrained, low cost and autonomous nodes that are distributed over an area for the purpose of monitoring or sensing the physical entities such as temperature, light, motion and humidity [16] [20][13]. Communication or relaying of data typically occurs via wireless multi-hop routing. The majority of WSNs described in the literature exhibit a (source, sink) architecture, which may include any number of:

Source nodes: which generate data, usually by using sensors to measure environmental factors such as temperature, humidity or radiation,

Sink nodes: which collect the data gathered by source nodes and

Intermediate nodes: which may include source nodes that aid the transmission from source to sink.

The generation of data at source nodes may occur either proactively or in response to some request. Sink nodes which are often referred to as base stations (BS), may be high powered, linked to databases via satellite links [12] or have more resources than other nodes. WSN nodes are typically battery powered and the energy capacity of a battery is dependent on its size and since nodes are expected to be small, the batteries are unlikely to be of high capacity. Battery depletion is one of the key challenges in developing and working with WSNs, particularly since every operation performed by the node requires expenditure of energy. While other resources such as the CPU and memory may be immediately re-used when released, the same is not true of the battery. Unless a node has some means of energy replenishment, the capacity of batteries restricts both the maximum lifetime of nodes and the frequency with which the node can carry out particular actions. Beyond these characteristics, it is difficult to provide a formal definition of the exact capabilities of a WSN, particularly due to the increasing number of scenarios making use of the technology [12]. It has been theorized that, with WSNs typically being application dependent, it is impossible to create a single architecture, which can be used in all applications [18].

Wireless technology has been traditionally used to connect people to each other or to devices. Cellular systems, wireless local area networks and broadband wireless access aim to provide voice and data communication. WSNs on the other hand have introduced a plethora of applications from traffic monitoring to health, from battlefield to surveillance and security by providing communication between devices. Recent developments in sensor technology and low power radios have enabled the widespread deployment of sensor networks consisting of small sensor nodes with sensing, computation, and communication and actuation capabilities. An individual sensor node collects data from the environment, performs local processing of data including quantization and compression, communicates its results to a data fusion center via a wireless medium and takes an action in response. Since a single sensor provides only limited information, a network of these sensors is used to manage large environments.

2. Challenges in Wireless Sensor Networks

The characteristics of sensor networks and requirements of different applications have a decisive impact on the network design objectives and challenges in terms of network capabilities and performance. Sensor nodes are small-scale devices with volumes approaching a cubic millimeter in the near future. Such small devices are very limited in the amount of energy they can store or harvest from the environment. Furthermore, nodes are subject to failures due to depleted batteries or, more generally, due to environmental influences. Limited size and energy also typically means restricted resources (CPU performance, memory, wireless communication bandwidth and range). Extending lifetime and energy efficiency are also important objectives and challenges in WSNs [9].

Node mobility, node failures and environmental obstructions cause a high degree of dynamics in WSN. This includes frequent network topology changes and network partitions. Despite partitions, however, mobile nodes can transport information across partitions by physically moving between them. However, the resulting paths of information flow might have unbounded delays and are potentially unidirectional.

Communication failures are also a typical problem of WSN. Another issue is heterogeneity. WSN may consist of a large number of rather different nodes in terms of sensors, computing power and memory. The large number raises scalability issues on the one hand, but provides a high level of redundancy on the other hand. Also, nodes have to operate unattended, since it is impossible to service a large number of nodes in remote, possibly inaccessible locations. The design and development of a successful network must address many challenges dictated by WSN characteristics on one hand and the applications on the other. Few major challenges are as follows:

Small Node Size: Reducing node size is one of the primary design objectives of sensor networks. The advent in microelectronics technology made it possible to design miniaturized devices on the order of one cubic centimeter. Limited in energy and individual resources (such as CPU and memory), these tiny devices could be deployed in hundreds or even thousands in harsh and hostile environments. Reducing node size can facilitate node deployment and also reduce the cost and power consumption of sensor nodes.

Low Node Cost: Reducing node cost is another primary design objective of sensor networks. Since sensor nodes are usually deployed in a harsh or hostile environment in large numbers and cannot be reused, it is important to reduce the cost of sensor nodes so that the cost of the whole network is reduced.

Low Power Consumption: Reducing power consumption is the most important objective in the design of a sensor network. Sensor nodes are powered by battery and it is often very difficult or even impossible to change or recharge their batteries. This constraint presents many new challenges in the development of hardware and software, and the design of network architectures and protocols for sensor networks. To prolong the operational lifetime of a sensor network, energy efficiency should be considered in every aspect of sensor network design [4][3].

Limited Hardware Resources: Sensor nodes have limited processing and storage capacities, and thus can only perform limited computational functionalities. These hardware constraints present many challenges in software development and network protocol design for sensor networks, which must consider not only the energy constraint in sensor nodes, but also the processing and storage capacities of sensor nodes.

Massive and Random Deployment: Most sensor networks consist of a large number of sensor nodes, from hundreds to thousands or even more. Node deployment is usually application dependent, which can be either manual or random. In most applications, sensor nodes can be scattered randomly in an intended area or dropped massively over an inaccessible or hostile region. The sensor nodes must autonomously organize themselves into a communication network before they start to perform a sensing task.

Dynamic and Unreliable Environment: A sensor network usually operates in a dynamic and unreliable environment. On one hand, the topology of a sensor network may change frequently due to node failures, damages, additions or energy depletion. On the other hand, sensor nodes are linked by a wireless medium, which is noisy, error prone and time varying. The connectivity of the network may be frequently disrupted because of channel fading or signal attenuation.

- **Diverse Applications:** Sensor networks have a wide range of diverse applications. The requirements for different applications may vary significantly. No network protocol can meet the requirements of all applications. The design of sensor networks is application specific.
- **Scalability:** Scalability measures the density of the sensor nodes. In sensor networks, the number of sensor nodes may be on the order of tens, hundreds or thousands. Thus, network protocols designed for sensor networks should be scalable to different network sizes.
- **Adaptability and Self Configurability:** In sensor networks, a node may fail, join or move which would result in changes in node density and network topology. Thus, network protocols designed for sensor networks should be adaptive to such density and topology changes. In sensor networks, sensor nodes are usually deployed in a region of interest without careful planning and engineering. Once deployed, sensor nodes should be able to autonomously organize themselves into a communication network and reconfigure their connectivity in the event of topology changes and node failures.
- **Heterogeneity:** Middleware should provide low-level programming models to meet the major challenge of bridging the gap between hardware technology's raw potential and the necessary broad activities such as reconfiguration, execution and communication. It should establish system mechanisms that interface to the various types of hardware and networks supported only by distributed, primitive operating-system abstractions.
- **Dynamic Network Organization and Applications:** Unlike traditional networks, sensor networks must deal with resources that are dynamic, such as energy, bandwidth and processing power. Sensor networks also must support long running applications, so routing protocols must be efficiently designed to enable the network to run as long as possible [14]. Because knowledge of the network is essential for it to operate properly, the efficient mechanisms are required to provide ad hoc network resource discovery. A sensor node needs to know its location in the network and in the whole network topology. In some cases, self-location by Global Positioning System (GPS) is impossible, unfeasible or expensive. Important system parameter issues such as network size and density per square mile, affect the trade offs among latency, reliability and energy. Most sensor network applications are real-time phenomena, where time and space are extremely important.
- **Data Aggregation:** Data aggregation is a widely used technique in WSNs. Most sensor network applications involve nodes that contain redundant data and are located in a specific local region. These traits open the possibility for in-network aggregation of data from different sources, eliminating redundancy and minimizing the number of transmissions to the sink. This aggregation saves considerable energy and resources; given that communication cost is much higher than computation cost.
- **Quality of S ervice (QoS):** In sensor networks, different applications may have different Quality - of - Service (QoS) requirements in terms of delivery latency and packet loss. For example, some applications like fire monitoring are delay sensitive and thus require timely data delivery whereas applications such as data collection for scientific exploration are delay tolerant but cannot stand packet loss. Thus, network protocol design should consider the QoS requirements of specific applications. QoS is an overused term with multiple meanings and perspectives from different research and technical communities. In WSNs, we can view QoS from two perspectives: application-specific and network. The former refers to QoS parameters specific to the application, such as sensor node measurement, deployment, coverage and number of active sensor nodes. The latter refers to how the supporting communication network can meet application needs while efficiently using network resources such as bandwidth and power consumption. Traditional QoS mechanisms used in wired networks are not adequate for WSNs because of constraints such as resource limitations and dynamic topology. Therefore, new mechanisms are to be provided to maintain QoS over an extended period and even adjust itself when the required QoS and the state of the application changes. Such mechanisms should be designed based on trade-offs among performance metrics such as network capacity or throughput, data delivery delay and energy consumption.
- **Security:** WSNs are being widely deployed in domains that involve sensitive information like healthcare and rescue. The untethered and large deployment of WSNs in harsh environments increases their exposure to malicious intrusions and attacks such as denial of service. In addition, the wireless medium facilitates eavesdropping and adversarial packet injection to compromise the network's functioning. All these factors make security extremely important. Sensor nodes have limited power and processing resources, so standard security mechanisms, which are heavy in weight and resource consumption, are unsuitable. These challenges increase the need to develop

comprehensive and secure solutions that achieve wider protection, while maintaining desirable network performance.

- **Delay Guarantee:** When the sensor node data are used to control a physical process, a guaranteed bound on the delay is necessary for effective control action, e.g. Traffic lights, fire detection, medical monitoring. The protocol may not be trusted without such a bound.
- **Channel Utilization:** Sensor networks have limited bandwidth resources. Thus, communication protocols designed for sensor networks should efficiently make use of the bandwidth to improve channel utilization.
- **Reliability:** For many sensor network applications, it is required that data be reliably delivered over noisy, error - prone and time - varying wireless channels. To meet this requirement, sensor networks must provide error control and correction mechanisms to ensure reliable data delivery.
- **Fault Tolerance:** Sensor nodes should be fault tolerant and have the abilities of self - testing, self - calibrating, self - repairing and self - recovering. The sensor network should tolerate three kinds of faults: sensor failure, node failure, link failure. Sensor failure results from imperfections in manufacturing or due to aging. The most easily detectable sensor fault is the one that is uncorrelated with the environmental changes. For instance, the sensor may be frozen to a particular value and we may only observe the receiver noise plus this constant value. This fault should be detected and the sensor readings should be ignored. The aging of the sensor on the other hand makes the variance of the readings degrade over time. Then the sensor readings may not be useful depending on the aging factor and application. Node failure may result from power loss or mobility while link failures are due to the movement of the nodes, which may not be applicable for most sensor network applications and the movement of the objects in the environment, such as the cars in a parking lot application.

3. Reliability in Wireless Sensor Network

Reliability in WSN reflects a functional unit's ability to meet performance specifications over a specified period of time and this is often expressed as a probability or mean time to failure (MTTF). Fault tolerance in WSN is the quality or ability of a functional unit to perform a required task in the presence of some number of faults or errors. The distinction is that the former is an attribute relating to the performance period until a fault is encountered while the latter is with regard to the system's performance in the presence of one or more failed components. Fault tolerance is applied to increase the reliability of a system.

4. Motivation

WSNs are still distrusted on reliability. Monitoring critical structures such as high speed railway bridges requires the monitoring network to be highly reliable. However, there is still a lack of reliability studies of WSNs as:

a) No attempt to define an accurate fault model from experimental evidence.
b) Fault forecasting methodologies have never been applied to WSNs.
c) The majority of research results are proved by means of simulation.
d) No attempt to make the sensor nodes intelligent enough to recall the information of interest despite of corrupted signal sensed at the destination and hence to enhance the reliability of communication.

The gap between industrial development and research activities can be reduced by clearly identifying the reliability requirements and related issues and challenges. To further reduce the distrust on reliability of WSNs and to assess risks and costs, fault forecasting also needs to be undertaken. WSN is exposed to several faults such as data packets may be lost or delivered with errors. Therefore, specific reliability requirements must be considered. Fault tolerance is also a critical issue for sensors deployed in place where they are not easily replaceable, repairable and rechargeable. The failure of one node should not incapacitate the entire network. If all sensors deployed within a small area are active simultaneously, an excessive amount of energy is used, redundant data is generated and packet collision can occur on transmitting data. At the same time, if areas are not covered, events can occur without being observed. A density control function is required to ensure that a subset of nodes is active in such a way that coverage and connectivity are maintained. Coverage refers to the total area currently monitored by active sensors in the network. Connectivity refers to the connectivity of the sensor network modeled as a graph where the currently active sensors have to form a fully connected graph such that the collected data can be relayed to the initiators (the nodes requesting data). The nodes in a wireless environment are greatly dependent on the battery life and power. Therefore, it is challenging to minimize energy consumption for a WSN, while keeping it functional is a major objective in designing a robust and reliable network.

5. Literature Survey

Reliability in sensor networks is multi-faceted and reliable data transport, a very important and interesting issue. The reliable data transport problem itself has also many faces, ranging from single packet delivery to delivery of periodic streams. Many of the protocols discussed in [11] attack the reliability problem by combining mechanisms on several layers, from the MAC layer up to the application layer. This is different from the Internet-way of thinking about reliability, but necessary when energy is at premium. It is also fair to say that reliability issues have so far attracted less attention in the research community than, say, MAC or routing protocols. There is accordingly plenty of room for interesting research, like for example: - (i) design and evaluation of further mechanisms for improving reliability, taking the complex behavior of wireless channels into account;

(ii) Experimental studies regarding reliability and energy-efficiency in real sensor networks [15] and (iii) consideration of timing-aspects [19].

Clustering is a key technique used to extend the lifetime of a sensor network by reducing energy consumption. Sensor nodes are considered to be homogeneous since the researches in the field of WSNs have been evolved, but some nodes may be of different energy to prolong the lifetime of a WSN and its reliability. Authors in [1] have studied the impact of heterogeneity of nodes to the performance of WSNs. In this research, authors have surveyed different clustering algorithms for heterogeneous WSNs by classifying algorithms depending upon various clustering attributes.

Authors in [5] offered a comprehensive theoretical study on the packet arrival probability and average energy consumption for retransmission and redundancy approaches to enhance data transmission reliability. Analysis indicates that when loss probability remains low or moderate, Erasure Coding, a scheme based on redundancy, is more reliable and energy efficient than retransmission. However, the performance of Erasure Coding would largely deteriorate under high packet loss condition. authors demonstrated that its resistance capability against packet loss weakens as hop number increases. Furthermore, with the increase in redundancy, Erasure Coding has to sacrifice the advantage of energy efficiency for reliability.

Different WSN applications require different grades of reliability. Communication protocols for WSN should be energy-efficient to avoid useless wasting of energy resources through minimization of the control and retransmission overhead; should have distributed functionality to exploit the WSN resources in cooperative way as proposed in [6], so that overall WSN operation is not hindered by the limited capacities of individual nodes; and should provide reliability differentiation to support different reliability grades in order to suit the requirements of different applications regarding throughput, latency and energy consumption.

In [8], authors considered the problem of how to measure the reliability of the large-scale wireless sensor networks, which is a fundamental requirement of wireless sensor networks deployment. Sensing coverage and network connectivity are key QoS requirements of wireless sensor networks, while network lifetime based on energy efficiency and invulnerability based on fault-tolerance are two main factors to measure network reliability. A novel reliability model to prolong the network lifetime and improve robust ability of wireless sensor network has been proposed in this research, which is based on certain K-Coverage and K-Connectivity constraints in order to support different QoS requirements with various applications or environments.

Authors in [2], proposed a routing algorithm for real-time wireless sensor networks using a hybrid algorithm that can increase reliability and network lifetime criterions. The results are compared with the presented algorithm in (Razzaque et al., 2006) applying the same conditions. Results demonstrate that the proposed algorithm in terms of reliability and network lifetime is more efficient.

Authors in [7] developed a reliability framework for data transport based on the different operational phases of the WSN protocols. For this, they established a fault model to capture the possible failures along with generalized data transport and reliability semantics and also developed a reliability block model based approach that exploits the decomposition of the complex data transport problem into operations and simplifies the investigation of the overall reliability of data transport.

Authors in [10] offered a contributing effort to explore the reliability issues in multi-fusion sensor networks. They presented Markov models of the reliability using different types of sensors and spares that replace sensors when failed.

For a moderate-size, multi-hop, sensor network, authors in [17] presented experimental measurements of radio energy consumption and packet reliability. They categorized the energy measurements by energy consumed in each radio state and for each traffic type. They introduced a novel technique of application-aware radio duty cycling called on-demand spatial TDMA. When compared to the non-cycling case, this technique can achieve greater than an order of magnitude reduction in idle energy consumption, while not sacrificing reliability. It is observed that end-to-end packet loss rates as low as 0.04 when averaged over the network.

6. Factors Affecting the Reliability in WSNs

- Hardware failure
- Inappropriate communication scheme
- Constrained resources in sensor nodes
- Error prone wireless communication medium

7. Research Objectives

- Sensing the environment and sending the sensed data to a remote place via sink with greater reliability is the primary objective of WSNs. In many applications like battlefield surveillance and forest fire detection, reliability is the primary concern and can not be compromised with cost of the network. So, there is need of using redundant sensor nodes as additional sensors to replace the faulty sensor nodes of the same type and thus to provide fault tolerance for the communication backbone.
- Many applications of WSNs require immediate and guaranteed actions like medical emergency alarm and fire detection. In these situations, packets has to be transported in a reliable way and in time through the sensor network and thus data reliability becomes very relevant for the proper functioning of the network. Most of the solutions available in literature address a specific reliability and fault tolerance problem but ignore other issues like fast delivery and successful transmission of packets in presence of some missing and mistaken bits due to noise, etc. in the communication channel.
- Number of algorithms have studied the use of encoding techniques to enhance the reliability of the communications like Reed-Solomon encoding, data encoding to combat channel fading and distributed classification fusion approach using error correcting codes. There is still scope to enhance the reliability of communications by using neural network based encoding and clustering techniques.
- There is a need of some mechanism to overcome the problems coming from wireless communication medium and limited resources. In WSNs, the medium of communication is wireless which is more unreliable than wired system as wireless channel is more noisy. Because of disturbances/ noise, the information of interest may not be delivered successfully at the destination.
- A sensor node is battery powered, so has limited power source and also it has small computational power and memory space. Therefore we can’t play complicated algorithm to achieve the reliability. We can’t send many control packets to tune the network, nor can we run sophisticated algorithm in sensor nodes.

8. Conclusion and Challenges Ahead

WSNs hold the promise of many applications in the area of monitoring and control systems. Many properties of the environment can be observed by the monitoring system with the advent of cheap and tiny sensors. All these applications are meant for the specific purposes, and therefore maintaining data transport reliability is one of the major concern and the most important challenge. To address the reliability, we survey the various existing techniques; each of them has its own unique working to ensure the reliability. Some of the techniques use retransmission mechanism while others use redundant information for insuring the reliability. Few of the above objectives may be considered in the future by the researchers. These objectives may be achieved as under:

- By developing a Markov based model with additional mobile sensors to replace the faulty sensors in case failure occurs.
- By developing the efficient mechanism for clustering the sensor nodes in heterogeneous WSNs to minimize the number of additional sensors required during the deployment based on artificial neural network models.
- By developing a model for reliable and quick packet delivery in WSNs to enhance the performance of the network using appropriate application dependent communication schemes.
- By developing a model for reliable and fault tolerant transmission by introducing biologically inspired sensor nodes which can be trained to memorize the possible events to be observed by the network. In this proposed model, we will use neural network based techniques as knowledge of artificial neural network is stored in its connections in the form of weights and hence no additional data storage will be required in the each sensor node. The proposed model will overcome the problems coming from limited memory and error prone wireless communication medium as the network can recall the lost memory (information of interest) from the biologically inspired sensor nodes based on chain of mental (already memorized system) associations despite of the corrupted signal sensed at the destination.

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